

Unparticle Physics and Supersymmetry Phenomenology

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Abstract

We show a natural form of the interaction between unparticle and supersymmetry. Using the couplings of unparticle to supersymmetry presented, as examples, we calculate the differential decay rates for the processes $\tilde{f} \rightarrow f + \mathcal{U}_{3/2}$, $\tilde{\chi}^0 \rightarrow \gamma + \mathcal{U}_{3/2}$, $\tilde{\chi}^\pm \rightarrow W^\pm + \mathcal{U}_{3/2}$ and $\tilde{\chi}^0 \rightarrow Z^0 + \mathcal{U}_{3/2}$. Finally, we discuss the phenomenological implication of our results and give some comments.

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I. INTRODUCTION

Very recently, Georgi suggested[1] that a scale invariant sector might be treated as an effective theory at TeV scale. He called it “unparticle”. Georgi assumed[1] that there is a high energy theory containing two parts. One contains the fields of the Standard Model(SM), while the other contains a theory with a nontrivial infrared fixed point, which will be a scale invariant sector at the infrared fixed point. An example of such theory is a four dimensional massless Yang-Mills theory with suitable fermion number. Actually, more than twenty years ago, Banks and Zaks had shown[2] that some massless Yang-Mills theory(\mathcal{BZ} fields) might have a nontrivial infrared fixed point. Georgi further pointed out[1] that if these two parts interact through the exchange of particles with a large mass scale M_U , below the scale M_U a nonrenormalizable coupling involving both SM fields and \mathcal{BZ} fields will be induced. And the renormalizable couplings of the \mathcal{BZ} fields then cause dimensional transmutation as the scale invariance in the \mathcal{BZ} sector emerges at an energy scale Λ_U , below which the \mathcal{BZ} operators match onto unparticle operators. Finally, one can obtain nonrenormalizable interactions of standard model operators with unparticle operators, and these effective interactions can be treated in the frame of effective field theory. Moreover, as shown by Georgi[1], scale invariance can be used to calculate the appropriate phase space for unparticle stuff. An important result is that unparticle stuff with scale dimension d_U looks like a nonintegral number d_U of invisible particles[1]. To understand this claim, we remember that the phase space for n massless particles is

$$(2\pi)^4 \delta^4 \left(P - \sum_{j=1}^n p_j \right) \prod_{j=1}^n \delta(p_j^2) \theta(p_j^0) \frac{d^4 p_j}{(2\pi)^3} = A_n \theta(P^0) \theta(P^2) (P^2)^{n-2}, \quad (1)$$

where

$$A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n+1/2)}{\Gamma(n-1)\Gamma(2n)}. \quad (2)$$

For an unparticle operator O_U with dimension d_U , the appropriate phase space can be written as[1]

$$|\langle 0 | O_U(0) | P \rangle|^2 \rho(P^2) = A_{d_U} \theta(P^0) \theta(P^2) (P^2)^{d_U-2}, \quad (3)$$

with

$$A_{d_U} = \frac{16\pi^{5/2}}{(2\pi)^{2d_U}} \frac{\Gamma(d_U+1/2)}{\Gamma(d_U-1)\Gamma(2d_U)}, \quad (4)$$

where $|P\rangle$ is the unparticle state with 4-momentum P^μ produced from the vacuum by O_U . This is a simple result of scale invariance. Using this formula and the virtual propagator

of unparticle[1], one can calculate some scattering cross sections and decay rates of the processes with unparticle.

Following Georgi, in a few months, various phenomenological implications on unparticle physics have been explored by many groups[3][4][5]. However, all of these studies are concerned with unparticles which couple to the SM sector through higher dimensional operators in low energy effective theory. In this paper we propose a scheme in which the supersymmetry fields and \mathcal{BZ} fields interact via the exchange of particles with a large mass scale M_U .

In fact, if unparticle appears at TeV scale, it will be worth to investigate the situation where the visible sector is not only SM but a TeV new physics, such as supersymmetry or extra dimension. The Minimal Supersymmetric Standard Model(MSSM) is a popular new physics candidate at TeV scale although we still do not know what is the TeV new physics. Only future experiment can answer this question. In this paper we first try to understand what we will see if the visible sector in Georgi's scheme[1] at TeV scale is MSSM.

II. SUPERSYMMETRY WITH UNPARTICLE

As we mentioned above, it is an interesting problem to study a supersymmetric visible sector in Georgi's scheme. However, there are many uncertainties to solve this problem. One of them is how MSSM operator couples to unparticle operator. In fact, we can choose this coupling freely. Different choices will lead to different phenomenologies. But we will present the natural couplings here and show some phenomenological results.

One of useful methods for constructing the couplings between supersymmetry and unparticle is to couple the supercurrent to an unparticle operator. As we know, for a Lagrangian density which includes both chiral and gauge superfields, the general form of the supercurrent is[6]

$$S^\mu = -\frac{1}{4} \sum_A f_{A\rho\sigma} [\gamma^\rho, \gamma^\sigma] \gamma^\mu \lambda_A - i \sum_{Anm} (t_A)_{nm} \gamma_5 \gamma^\mu \lambda_A \phi_n^* \phi_m + \frac{1}{\sqrt{2}} \sum_n [(\not{D}\phi)_n \gamma^\mu \psi_{nR} + (\not{D}\phi^*)_n \gamma^\mu \psi_{nL} + 2 \left(\frac{\partial W(\phi)}{\partial \phi_n} \right) \gamma^\mu \psi_{nL} + 2 \left(\frac{\partial W(\phi)}{\partial \phi_n} \right)^* \gamma^\mu \psi_{nR}], \quad (5)$$

where $f_{\mu\nu}$ is gauge field, λ is gaugino field, t_A is the generator of the gauge group, ϕ is the scalar component fields of chiral superfields, the superpartners of ϕ and ϕ^* are ψ_L and

ψ_R (they are Majorana spinors), $W(\phi)$ is the superpotential of chiral superfields. Since the supercurrent is a spin- $\frac{3}{2}$ fermion operator, the unparticle operator must be a spin- $\frac{3}{2}$ fermion operator too in order to get a Lorentz invariant interaction. Thus this interaction can be written as

$$C_{\mathcal{U}} \frac{\Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}} - d_{\mathcal{U}}}}{M_{\mathcal{U}}^k} \bar{S}_{\mu} \mathcal{U}_{3/2}^{\mu} + h.c., \quad (6)$$

where $\mathcal{U}_{3/2}^{\mu}$ is the spin- $\frac{3}{2}$ unparticle operator with the scaling dimension $d_{\mathcal{U}}$, $C_{\mathcal{U}}$ is a coefficient function, $d_{\mathcal{BZ}}$ is mass dimension of \mathcal{BZ} operator.

We now calculate some sparticles decay processes from Eq.(6). The general differential decay rate is

$$d\Gamma = \frac{|\mathcal{M}|^2}{2M} d\Phi(P), \quad (7)$$

where

$$d\Phi(P) = \int (2\pi)^4 \delta^4 \left(P - \sum_j p_j \right) \prod_j d\Phi(p_j) \frac{d^4 p_j}{(2\pi)^4}. \quad (8)$$

For an unparticle, the final state density is[1]

$$d\Phi_{\mathcal{U}}(p_{\mathcal{U}}) = A_{d_{\mathcal{U}}} \theta(p_{\mathcal{U}}^0) \theta(p_{\mathcal{U}}^2) (p_{\mathcal{U}}^2)^{d_{\mathcal{U}}-2}. \quad (9)$$

When we consider the scale invariance violation of the unparticle stuff, the final state density is[4]

$$d\Phi_{\mathcal{U}}(p_{\mathcal{U}}) = A_{d_{\mathcal{U}}} \theta(p_{\mathcal{U}}^0) \theta(p_{\mathcal{U}}^2 - \mu^2) (p_{\mathcal{U}}^2 - \mu^2)^{d_{\mathcal{U}}-2}, \quad (10)$$

where μ is a mass scale at which the scale invariance of the unparticle stuff is violated. When we calculate the spin sums of the squared matrix element, we need the polarization sums formula of the unparticle, which can be written as

$$\alpha g^{\mu\nu} \not{p}' + \beta (p^{\mu} \gamma^{\nu} + \gamma^{\mu} p^{\nu}), \quad (11)$$

where p^{μ} is the momentum of the unparticle and α and β are free parameters. Using Eqs.(5)-(11), it is straightforward to calculate several decay rates involving unparticles in final states as follows.

(1). $\tilde{f} \rightarrow f + \mathcal{U}_{3/2}$: The sfermion-fermion-unparticle coupling is given by

$$\bar{\mathcal{U}}_{3/2\mu} (\partial \tilde{f}_L^*) \gamma^{\mu} P_L f + \bar{\mathcal{U}}_{3/2\mu} (\partial \tilde{f}_R^*) \gamma^{\mu} P_R f + m_f \bar{\mathcal{U}}_{3/2\mu} \tilde{f}_R^* \gamma^{\mu} P_L f + m_f \bar{\mathcal{U}}_{3/2\mu} \tilde{f}_L^* \gamma^{\mu} P_R f + h.c.. \quad (12)$$

The decay width for this process is

$$\Gamma = \frac{(4\beta - \alpha)A_{d_U}C_{\mathcal{U}}^2\Lambda_{\mathcal{U}}^{2(d_{\mathcal{B}Z}-d_U)}m_f^{d_U+1/2}}{2\pi^2a^{d_U+3/2}m_{\tilde{f}}^{7/2-d_U}M_{\mathcal{U}}^{2k}}[a^2m_f(m_{\tilde{f}}^2 - m_f^2)f_0(a, d_U) + am_{\tilde{f}}(m_{\tilde{f}}^2 + m_f^2)f_1(a, d_U) - 2m_{\tilde{f}}^2m_ff_2(a, d_U)]\theta(m_{\tilde{f}} - m_f - \mu), \quad (13)$$

with

$$f_0(a, d) = 4^{-d}(1 - 4a^2)^{d-1}a^{3/2-d}\sqrt{\pi}\Gamma\left(d - \frac{3}{2}\right) {}_2\tilde{F}_1\left(\frac{1}{4}(2d - 3), \frac{1}{4}(2d + 1); d; 1 - \frac{1}{4a^2}\right) \quad (14)$$

$$f_1(a, d) = 4^{-d}(1 - 4a^2)^{d-1}a^{5/2-d}\sqrt{\pi}\Gamma\left(d - \frac{3}{2}\right) {}_2\tilde{F}_1\left(\frac{1}{4}(2d - 5), \frac{1}{4}(2d + 3); d; 1 - \frac{1}{4a^2}\right) \quad (15)$$

$$f_2(a, d) = -2^{-d-\frac{7}{2}}\sqrt{\pi}\Gamma\left(d - \frac{3}{2}\right) G_{3,3}^{2,1}\left(4a^2 \middle| \begin{matrix} \frac{3}{2}, \frac{1}{4}(2d + 5), \frac{1}{4}(2d + 7) \\ 0, 2, \frac{5}{2} \end{matrix} \right), \quad (16)$$

where $\theta(z)$ is the Heaviside function, m_f is the fermion mass, $m_{\tilde{f}}$ is the sfermion mass, $a = \frac{m_fm_{\tilde{f}}}{m_{\tilde{f}}^2+m_f^2-\mu^2}$, $x = \frac{m_{\tilde{f}}E_f}{m_{\tilde{f}}^2+m_f^2-\mu^2}$ and E_f is the energy of the final state fermion in the center of mass system. ${}_2\tilde{F}_1(a, b; c; z)$ is the regularized hypergeometric function. $G_{p,q}^{m,n}\left(z \middle| \begin{matrix} a_1, \dots, a_p \\ b_1, \dots, b_q \end{matrix} \right)$ represents the Meijer G function. And the dimensionless differential decay rate is

$$\begin{aligned} \frac{m_{\tilde{f}}d\Gamma}{\Gamma dE_f} = & am_{\tilde{f}}[a^2m_f(m_{\tilde{f}}^2 - m_f^2) + am_{\tilde{f}}(m_{\tilde{f}}^2 + m_f^2)x - 2m_{\tilde{f}}^2m_fx^2] \\ & (1 - 2x)^{d_U-5/2}(x^2 - a^2)^{1/2}\theta(1 - 2x)m_f^{-1}[a^2m_f(m_{\tilde{f}}^2 - m_f^2)f_0(a, d_U) \\ & + am_{\tilde{f}}(m_{\tilde{f}}^2 + m_f^2)f_1(a, d_U) - 2m_{\tilde{f}}^2m_ff_2(a, d_U)]^{-1}. \end{aligned} \quad (17)$$

In the limit of the zero fermion mass, the dimensionless differential decay rate is reduced to

$$\frac{m_{\tilde{f}}d\Gamma}{\Gamma dE_f} = \frac{4\Gamma(d + 3/2)\Gamma(d + 5/2)m_{\tilde{f}}^2[m_{\tilde{f}}^2x^2 - 2(m_{\tilde{f}}^2 - \mu^2)x^3](1 - 2x)^{d_U-\frac{5}{2}}\theta(1 - 2x)}{\Gamma(d - 3/2)(m_{\tilde{f}}^2 - \mu^2)[m_{\tilde{f}}^2\Gamma(d + 5/2) - 3(m_{\tilde{f}}^2 - \mu^2)\Gamma(d + 3/2)]}. \quad (18)$$

(2). $\tilde{\chi}^0 \rightarrow \gamma + \mathcal{U}_{3/2}$: The gaugino-photon-unparticle coupling is

$$\bar{\mathcal{U}}_{3/2\mu}F_{\rho\sigma}^A[\gamma^\rho, \gamma^\sigma]\gamma^\mu\tilde{\chi}_A + h.c., \quad (19)$$

where $\tilde{\chi}_A$ is the gaugino, from which it is easy to get a mass eigenstate, and $F_{\rho\sigma}^A$ is the field strength of the gauge field. The decay width is given by

$$\Gamma = -\frac{3\alpha A_{d_U}C_{\mathcal{U}}^2\Lambda_{\mathcal{U}}^{2(d_{\mathcal{B}Z}-d_U)}(m_{\tilde{\chi}^0}^2 - \mu^2)^{d_U+3/2}\Gamma\left(d_U - \frac{3}{2}\right)}{16\pi^2m_{\tilde{\chi}^0}^3M_{\mathcal{U}}^{2k}\Gamma\left(d_U + \frac{5}{2}\right)}\theta(m_{\tilde{\chi}^0} - \mu), \quad (20)$$

where $m_{\tilde{\chi}^0}$ is the mass of neutralino, $x = \frac{m_{\tilde{\chi}^0} E_\gamma}{m_{\tilde{\chi}^0}^2 - \mu^2}$ and E_γ is the energy of the final state photon in the center of mass system. And the dimensionless differential decay rate is

$$\frac{m_{\tilde{\chi}^0} d\Gamma}{\Gamma dE_\gamma} = \frac{8m_{\tilde{\chi}^0}^2 \Gamma(d_U + \frac{5}{2})}{3(m_{\tilde{\chi}^0}^2 - \mu^2) \Gamma(d_U - \frac{3}{2})} (1 - 2x)^{d_U - \frac{5}{2}} x^3 \theta(1 - 2x). \quad (21)$$

(3). $\tilde{\chi}^0 \rightarrow Z^0 + \mathcal{U}_{3/2}$, $\tilde{\chi}^\pm \rightarrow W^\pm + \mathcal{U}_{3/2}$: The gaugino- Z^0 (W^\pm)-unparticle couplings have been shown in Eq.(19), and the corresponding decay widths are given by

$$\Gamma = -\frac{\alpha A_{d_U} C_U^2 \Lambda_U^{2(d_{BZ} - d_U)} m_G^{d_U + 3/2}}{2\pi^2 a^{d_U + 3/2} m_{\tilde{\chi}}^{5/2 - d_U} M_U^{2k}} [m_{\tilde{\chi}} f_2(a, d_U) - a m_G f_1(a, d_U)] \theta(m_{\tilde{\chi}} - m_G - \mu), \quad (22)$$

where $m_{\tilde{\chi}}$ and m_G are the masses of the neutralino(chargino) and the gauge boson(Z^0 or W^\pm), respectively, $a = \frac{m_G m_{\tilde{\chi}}}{m_{\tilde{\chi}}^2 + m_G^2 - \mu^2}$, $x = \frac{m_{\tilde{\chi}} E_G}{m_{\tilde{\chi}}^2 + m_G^2 - \mu^2}$ and E_G is the energy of the final state of gauge boson in the center of mass system. And the dimensionless differential decay rates are

$$\frac{m_{\tilde{\chi}} d\Gamma}{\Gamma dE_G} = \frac{a m_{\tilde{\chi}} (m_{\tilde{\chi}} x^2 - a m_G x)}{m_G [m_{\tilde{\chi}} f_2(a, d_U) - a m_G f_1(a, d_U)]} (1 - 2x)^{d_U - 5/2} (x^2 - a^2)^{1/2} \theta(1 - 2x). \quad (23)$$

III. DISCUSSIONS AND COMMENTS

We now present some numerical results for the differential decay rates of sparticles. We first plot the dimensionless differential decay rate $\frac{m_f d\Gamma}{\Gamma dE_f}$ versus $\frac{m_f E_f}{m_f^2 + m_f^2 - \mu^2}$ according to Eqs.(14)-(18) for different masses of sfermion and fermion, which are shown in Figs.1-3. From these figures, we can see that the shapes of the curves in Figs.2-3 are nearly the same, which shows that if the final state fermion is light, the zero mass limit is a good approximation.

It is an interesting signal at future colliders that a neutralino decays into a single photon plus missing energy. As we have pointed out, this decay can only happen when the mass of the neutralino is larger than μ . We calculate the differential decay rate of this process and show the dependence of the dimensionless differential decay rate $\frac{m_{\tilde{\chi}^0} d\Gamma}{\Gamma dE_\gamma}$ on $\frac{m_{\tilde{\chi}^0} E_\gamma}{m_{\tilde{\chi}^0}^2 - \mu^2}$ in Fig.4. Compared with Fig.3, it can be found that when d_U increases the unparticle carries less energy than one in the sfermion decay processes.

The dependence of the dimensionless differential decay rates of neutralino(chargino) decays into Z^0 (W^\pm) plus missing energy on $\frac{m_{\tilde{\chi}} E_G}{m_{\tilde{\chi}}^2 + m_G^2 - \mu^2}$ is shown in Figs.5-6. Since the decay can only happen for $m_{\tilde{\chi}} + m_G \geq \mu$, we choose a relative heavy neutralino(chargino).

In a word, our calculations show that a general property of sparticle decays into unparticle is that the energy of final state can change continuously, while the curve of the energy change of final state should be a delta function in two body decay of a massive particle in ordinary case. Actually, this is a consequence of scale invariance. This property could help us detect unparticle at future colliders. As $d_U \rightarrow \frac{3}{2}$ from above, in general we can see the curves become more peaked at $\frac{m_f E_f}{m_f^2 + m_f^2 - \mu^2} = 0.5$ or $\frac{m_{\tilde{\chi}} E_G}{m_{\tilde{\chi}}^2 + m_G^2 - \mu^2} = 0.5$, as the case shown in Ref.[1]. This means that when the dimension of the unparticle operator approximates to that of the corresponding particle operator, the behavior of unparticle looks like one of particle. We can also find that the shapes of the curves depend sensitively on d_U , which can help us identify the dimension of the unparticle operator. If the signals with those characters are discovered at future colliders, it will be useful for further understanding both unparticle and supersymmetry.

Finally, we make some comments as following:

1. Although the superpotential of MSSM is still R -parity conservation, the R -parity is apparently violated by the effective coupling of the supercurrent to the unparticle operator, which leads that the Lightest Supersymmetry Particle(LSP) in MSSM is not absolutely stable in this scenario. Thus, the LSP could not be a good candidate of dark matter. However, if the scale invariance of unparticle stuff is broken at some energy scale μ , which is below TeV but larger than the mass of the LSP, the LSP can not decay into an unparticle, and would be stable. And the LSP could be still a candidate of dark matter.

2. Since we coupled the unparticle operator to the supercurrent of MSSM, those couplings break supersymmetry explicitly. Actually, because the unparticle appears at TeV scale where supersymmetry has been broken, it dose not take the responsibility for supersymmetry breaking. Another interesting problem is how the unparticle stuff affects the invisible sector and the messenger of supersymmetry breaking[7]. However, this is beyond the scope of this paper.

3. Obviously, the constraints from electroweak precise observations to these couplings should be considered. It is also important to calculate using those couplings some processes at future colliders and some astrophysics processes which are relevant to dark matter and γ -ray burst. We leave these necessary tasks for a future work[8]. Our interest here was to

introduce new couplings of the unparticle to the supercurrent in MSSM and discuss some main points concerning its phenomenology.

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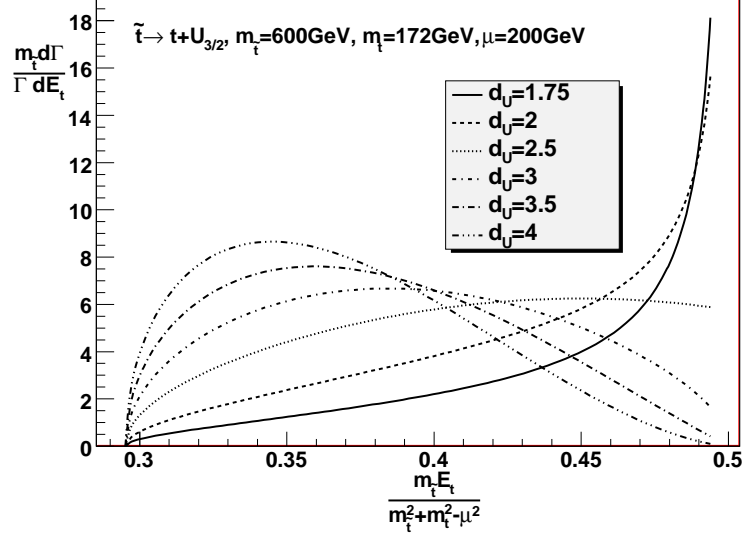


FIG. 1: The dimensionless differential decay rate $\frac{m_t d\Gamma}{\Gamma dE_t}$ versus $\frac{m_t E_t}{m_t^2 + m_t^2 - \mu^2}$ for different values of d_U .

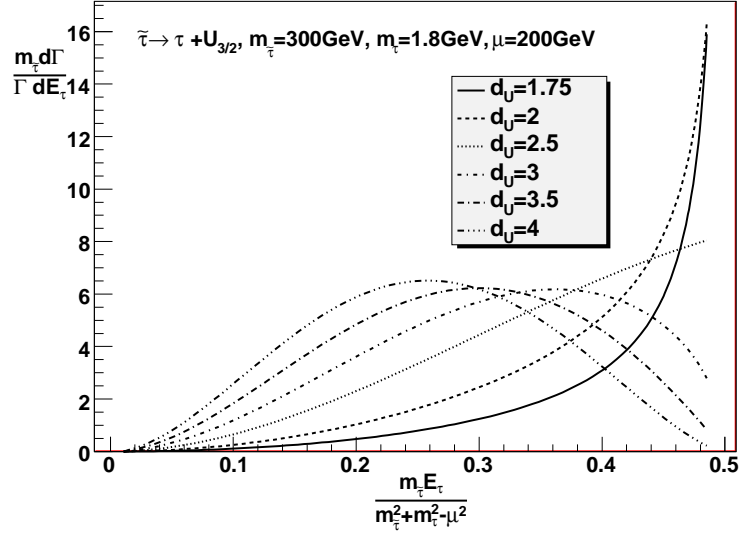


FIG. 2: The dimensionless differential decay rate $\frac{m_\tau d\Gamma}{\Gamma dE_\tau}$ versus $\frac{m_\tau E_\tau}{m_\tau^2 + m_\tau^2 - \mu^2}$ for different values of d_U .

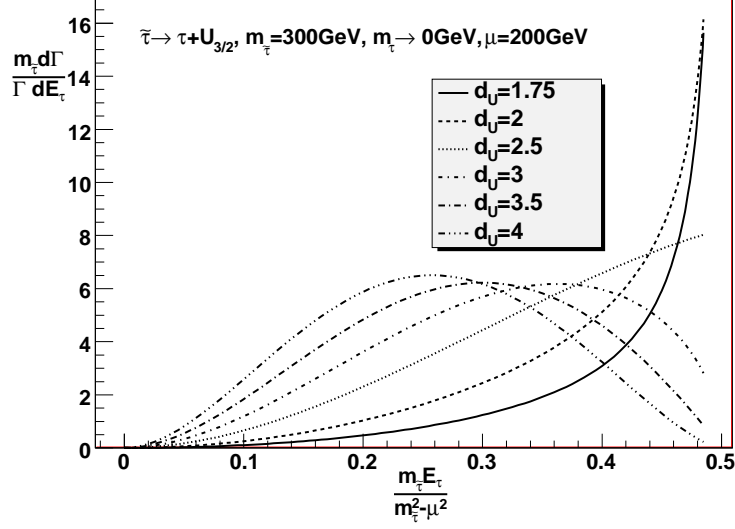


FIG. 3: The dimensionless differential decay rate $\frac{m_{\tilde{\tau}} d\Gamma}{\Gamma dE_{\tilde{\tau}}}$ versus $\frac{m_{\tilde{\tau}} E_{\tilde{\tau}}}{m_{\tilde{\tau}}^2 - \mu^2}$ for different values of d_U in the zero mass limit of tau.

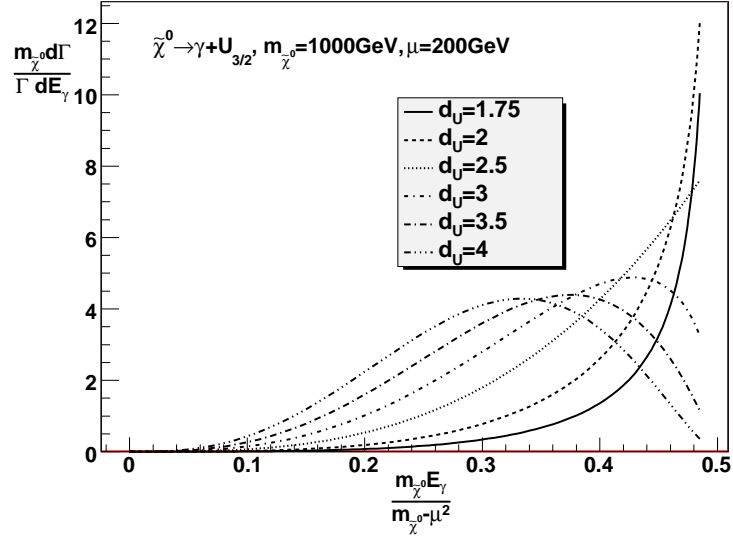


FIG. 4: The dimensionless differential decay rate $\frac{m_{\tilde{\chi}^0} d\Gamma}{\Gamma dE_{\gamma}}$ versus $\frac{m_{\tilde{\chi}^0} E_{\gamma}}{m_{\tilde{\chi}^0}^2 - \mu^2}$ for different values of d_U .

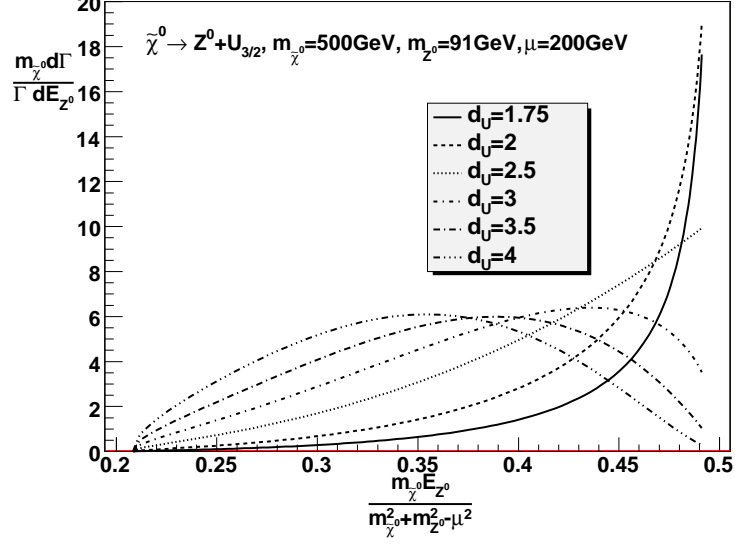


FIG. 5: The dimensionless differential decay rate $\frac{m_{\tilde{\chi}^0} d\Gamma}{\Gamma dE_{Z^0}}$ versus $\frac{m_{\tilde{\chi}^0} E_{Z^0}}{m_{\tilde{\chi}^0}^2 + m_{Z^0}^2 - \mu^2}$ for different values of d_U .

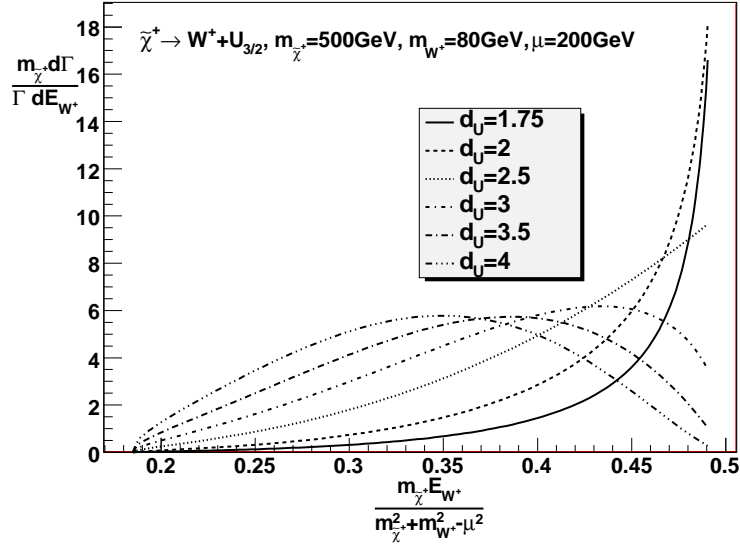


FIG. 6: The dimensionless differential decay rate $\frac{m_{\tilde{\chi}^+} d\Gamma}{\Gamma dE_{W^+}}$ versus $\frac{m_{\tilde{\chi}^+} E_{W^+}}{m_{\tilde{\chi}^+}^2 + m_{W^+}^2 - \mu^2}$ for different values of d_U .